Search for Θ^{++} Pentaquarks in the Exclusive Reaction $\gamma p \to K^+K^-p$

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The reaction $\gamma p \to pK^+K^-$ was studied at Jefferson Lab with photon energies from 1.8 to 3.8 GeV using a tagged photon beam. The goal was to search for a Θ^{++} pentaquark, a narrow doubly charged baryon state having strangeness S=+1 and isospin I=1, in the pK^+ invariant mass spectrum. No statistically significant evidence of a Θ^{++} was found. Upper limits on the total and differential production cross section for the reaction $\gamma p \to K^-\Theta^{++}$ were obtained in the mass range from 1.5 to 2.0 GeV/c^2, with an upper limit of about 0.15 nb, 95% C.L. for a narrow resonance with a mass $M_{\Theta^{++}} = 1.54$ GeV/c^2. This result places a very stringent upper limit on the Θ^{++} width.

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Since the first reports of possible observations of a Θ^+ pentaquark, a narrow baryon state having strangeness S=+1, there has been a great deal of speculation about its isospin structure [1, 2, 3, 4, 5, 6, 7, 8, 9]. If it were an isotriplet (I=1), one might expect to observe its isospin partners, in particular Θ^0 and Θ^{++}. For example, Roberts [5] calculated the production of pentaquarks in an isobar approach for all scenarios of spin, isospin and parity. It was concluded that an isovector pentaquark should have a cross section comparable with an isoscalar pentaquark, and if the Θ^+ is indeed isovector, one should expect to observe a comparable Θ^{++} cross section. However, on the experimental side, evidence of the existence of a Θ^{++} had not been forthcoming. Gibbs [10], analyzing available K^+p total cross sections, finds no evidence for an isovector resonance. Meanwhile, the standard PWA of the elastic KN scattering suggests [11] at least two Θ^{++} states, but very broad and with masses much higher than that of the Θ^+. Modification of this PWA [9] provides a whole set of candidates for the Θ^{++}, in particular, near the Θ^+ mass. But all those states, if confirmed, should be very narrow, having elastic widths less than 0.1 MeV.

Other experiments involving electromagnetic probes, (CLAS [12, 13], ZEUS [14], SAPHIR [15], and HERMES [16]), reported that no statistically significant signal for the Θ^{++} decaying to pK^+ was observed, even though each reported positive observations for candidate Θ^+ peaks. Indeed, although positive observations of the Θ^+ were reported in several laboratories, many others have seen no evidence of it, and its existence has become questionable. It has been noted that most of the reported negative results were based on high energy experiments involving pK^0 invariant mass reconstructions within large backgrounds of reaction fragments. Thus, it was speculated that even if a pentaquark does exist, a possible interpretation for non-observation in such experiments is that there would be a small probability for pentaquark formation, either I=0 or 1, since most of the quarks necessary to construct them would have to be created within the evolution of the reaction itself. However, recent reports of several exclusive follow-up experiments at lower energies at CLAS [17, 18] failed to verify earlier reported Θ^+ pentaquark signals observed at SAPHIR [15] and CLAS [19] . Moreover, a Θ^{++} search at Jefferson Lab Hall-A [20] using high-resolution limited-acceptance magnetic spectrometers studied the exclusive reaction $ep \to e'K^-(\Theta^{++})$ with no observation of a Θ^{++}

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peak. One can summarize that, unlike the situation of the Θ^+, which itself remains highly controversial, there had been no positive reports of the possible existence of a Θ^{++}.

Recently the issue of an isovector pentaquark was revitalized by the report of possible signals for Θ^{++} and anti-Θ^{++} ($\bar{\Theta}^{++}$) observed in d-Au and Au-Au interactions by the STAR Collaboration [21] at RHIC, in the invariant mass spectra of detected pK^+ and $\bar{p}K^-$ pairs, respectively. The reaction was inclusive since the high-energy beams (200 GeV/c for d-Au collisions) resulted in very large final state multiplicities producing a large underlying combinatoric background. The subtraction of the background yielded a 3.5σ to 5σ peak at 1.53 GeV/c^2. Although the peak was observed in d-Au collisions, there were no significant peaks observed from Au-Au and Cu-Cu collisions. Also, in such a highly inclusive reaction it is impossible to know if there are any associated particles, and whether the production is in the direct formation, or in the final state of a multi-step process. Thus, it would be advantageous to perform an experiment in which the initial state is carefully controlled, the final state is exclusively measured, and with large acceptance to include as much phase space as possible.

A feature of all positive observations of pentaquarks is that the signals contained very limited statistics. In this letter we report the results of a high statistics search for the production of the Θ^{++} state in the reaction $\gamma p \to K^-\Theta^{++}$, with $\Theta^{++} \to pK^+$. The experiment was performed at the Jefferson Lab CLAS facility. Details of the design and operation of the CLAS spectrometer and its components may be found in Ref. [22] and references within. Reference [23] discusses the experimental setup used in the present study in greater detail. An energy tagged bremsstrahlung beam produced by a continuous 60 nA electron beam of energy $E_0 = 4.02$ GeV, impinging on a gold radiator of thickness 8×10^{-5} radiation lengths, yielded incident photons in the energy range 1.8 to 3.8 GeV. The photon energy for each event was determined by means of a tagger placed upstream of the CLAS spectrometer. The photon energy resolution was approximately $0.1\% \times E_0$. The reaction target consisted of liquid hydrogen contained in a cylindrical mylar cell of length 40 cm.

Charged particles were detected by the CLAS spectrometer. Particle tracking utilized multiwire drift chambers and a toroidal magnetic field. Particle identification was primarily obtained by comparing the particle momentum with that calculated from the track length and flight time between scintillator detectors around the target and scintillator detectors surrounding the CLAS spectrometer. The CLAS momentum resolution is of the order of 0.5-1% (σ) depending on the kinematics. The detector's geometrical acceptance for positively charged particles in the relevant kinematic region is about 40%, and several times smaller for low energy negative hadrons, which can be lost at forward angles because they are bent out of the acceptance by the toroidal field. For example, the number of $\Lambda(1520)$ obtained by the reconstruction of pK^- events is almost an order of magnitude smaller than the number reconstructed from the missing mass of K^+ when the K^- is not required to be detected. Coincidences between the photon tagger and two charged particles in the CLAS detector triggered the recording of the events. The interaction time between the incoming photon and the target was measured by the start counter [24], consisting of a set of 24 2.2 mm thick plastic scintillators surrounding the hydrogen cell. An integrated luminosity of 70 pb^{-1} was accumulated in 50 days of running.

Due to the high degree of exclusivity, the reaction $\gamma p \to K^-\Theta^{++} \to K^-K^+p$ was studied in two ways: 1) Requiring detection of all three final state hadrons pK^-K^+ and then directly observing the invariant mass of the pK^+. 2) Detecting a pK^+ pair and identifying the K^- by missing mass reconstruction. Fig. 1 compares the K^- spectra obtained by each method. The upper panel shows the missing mass spectrum of the detected pK^+ in Case 1, in which all three final state hadrons, p, K^- and K^+, are required to be detected. The complete dominance of the K^- peak with small background indicates that nearly all the events are in the exclusive 3-body final state. The lower panel shows the missing mass spectrum of the detected pK^+ in Case 2, in which only the p and K^+ are required to be detected. The significant background underlying the K^- peak is mostly due to the misidentification of pions as kaons. In both cases a cut of 3σ around the K^- peak was imposed on the events which were retained for further analysis.

Figure 2 shows the invariant mass of the pK^- pairs after application of the cut on the K^- peak. The upper panel displays the invariant mass spectrum for the pK^- for events for Case 1 and the lower panel displays the missing mass in Case 2. The most notable feature in each spectrum is the prominent peak due to the $\Lambda(1520)$. In comparing the upper and lower panels of Figs. 1 and 2 it is observed that almost an order of magnitude in statistics is gained due to the increased acceptance in requiring only the detection of the p and K^+. There are nearly 1 million events corresponding to the $\Lambda(1520)$ peak for Case 2. The trade-off is that the pion contamination is significantly greater for Case 2 than Case 1. In addition to greater statistics, Case 2 has an advantage in that the undetected K^- can be emitted at any value of $\cos\theta_{CM}$, where θ_{CM} is the angle between the electron beam direction and pK^+ system in the center-of-mass system, so that the acceptance is significant in the entire range of $\cos\theta_{CM}$, from -1 to +1, and t-channel processes are not suppressed. On the other hand, in Case 1 the acceptance in $\cos\theta_{CM}$ for detecting the K^-s becomes smaller near $\cos\theta_{CM}$=+1, so that t-channel processes are suppressed.

In all further analysis, 3σ cuts were applied in the pK^- and K^+K^- mass spectra to eliminate the contribution of the $\Lambda(1520)$ and $\phi(1020)$, respectively.

The pK^+ mass spectra after all cuts were applied are shown for Case 1 and Case 2, in the upper and lower

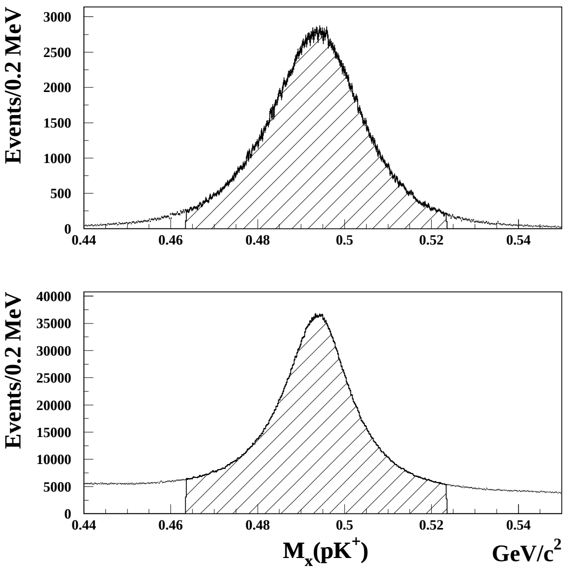

FIG. 1: The missing mass spectrum of pK^+ pairs. Upper panel: for events when all three final state particles, p, K^+ and K^-, are detected. Lower panel: for events when only the p and K^+ are required to be detected. Note the suppression of background in the upper panel compared with the lower panel, in which the background is dominated by misidentification of pions as kaons. The shaded regions correspond to 3σ cuts which define the region of retained events.

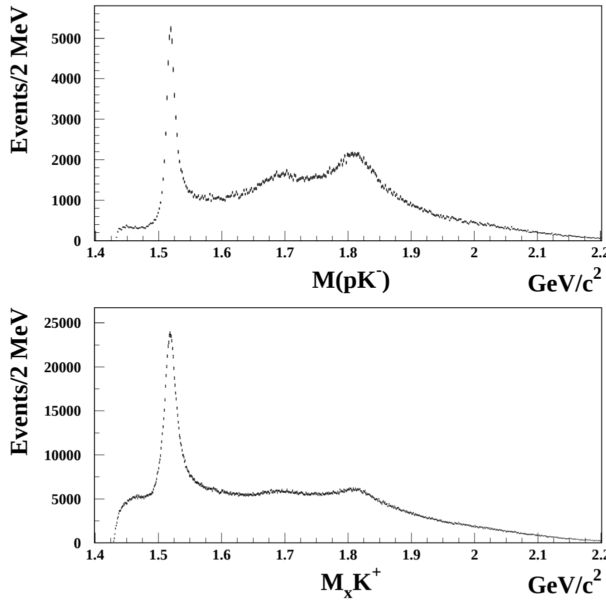

FIG. 2: Upper panel: The invariant mass spectrum for the pK^- for events when all three final state particles, p, K^+ and K^-, are detected. The most notable structure is the $\Lambda(1520)$ peak. Lower panel: The pK^- mass reconstructed from the missing mass of the detected K^+ for events in which only the p and K^+ are required to be detected. Events due to the $\Lambda(1520)$, as well as those due to $\phi(1020)$ in the K^+K^- spectra were removed from further analysis. The smaller number of $\Lambda(1520)$ events in the upper spectrum can be attributed to the much smaller acceptance for detection of the additional K^-.

panels of Fig. 3, respectively. In neither case is there any visual evidence for any narrow structures which could be interpreted as due to a Θ^{++}. The insets show expanded views in the region where one might expect a Θ^{++} partner of an isovector Θ^+ located near $M = 1.54$ GeV/^{2}. The pK^+ mass resolution $\sigma(M_{\Theta^{++}})$ varies as a function of the mass from 2 MeV/c^2 at $M_{\Theta^{++}} = 1.5$ GeV/c^2, up to 5.5 MeV/c^2 at $M_{\Theta^{++}} = 2.0$ GeV/c^2.

As for the $\Lambda(1520)$, the acceptance of the undetected K^- is significant at all center-of-mass angles. Thus, invariant mass spectra for pK^+ pairs were also obtained for discrete intervals of the center-of-mass angles of the emitted K^- (or pK^+ pairs) covering the entire angular range. No indication of a Θ^{++} peak is observed in any angular region.

Since no positive signal was observed, upper limits for the cross sections were determined for Case 2. Case 2 was chosen rather that Case 1 since there are no gaps in the acceptance, and statistics is much higher. Two methods were employed. In the first (Method 1), a Gaussian peak corresponding to $N_{\Theta^{++}}$, and a polynomial background were fit to the pK^+ spectrum for an assumed Θ^{++} mass, $M_{\Theta^{++}}$. Then a Feldman-Cousins [25] algorithm was applied to the number under the fit peak and background in a $\pm 3\sigma$ interval to obtain an upper limit of Θ^{++} events ($N^{95\%}_{\Theta^{++}}$) at the 95% confidence level (CL) . This was repeated as a function of $M_{\Theta^{++}}$. In the second method (Method 2), the pK^+ spectrum was fit with a polynomial, excluding the region of $M_{\Theta^{++}}$. For each $M_{\Theta^{++}}$ the $N_{\Theta^{++}}$ was obtained as the difference between the polynomial and the total number of events within a $\pm 3\sigma$ interval around $M_{\Theta^{++}}$. Again, this was analyzed with the Feldman-Cousins [25] algorithm. The cross section upper limit at the 95% level was then obtained from:

$$\sigma^{95\%}_{\Theta^{++}} = \frac{N^{95\%}_{\Theta^{++}}}{L(M_{\Theta^{++}}) \cdot \epsilon(M_{\Theta^{++}}) \cdot BR(\Theta^{++} \to pK^+)},$$

where $L(M_{\Theta^{++}})$ is the integrated luminosity for photons in the energy range from threshold for a given mass to 3.8 GeV, $\epsilon(M_{\Theta^{++}})$ is the pK^+ acceptance, and $BR(\Theta^{++} \to pK^+)$ is the branching ratio for $\Theta^{++} \to pK^+$, which is assumed to equal 1 for an isovector Θ^{++}.

This procedure was repeated as a function of $M_{\Theta^{++}}$ and as a function of $\cos\theta_{CM}$ at $M_{\Theta^{++}}$ =1.54 GeV/c^2. The upper limits obtained in Method 1 and Method 2 were found to be consistent. Since the mass resolution $\sigma(M_{\Theta^{++}})$ varies approximately linearly, increasing with $M_{\Theta^{++}}$, the variation in $\sigma(M_{\Theta^{++}})$ and the acceptance $\epsilon(M_{\Theta^{++}})$ as a function of $M_{\Theta^{++}}$ were taken into account

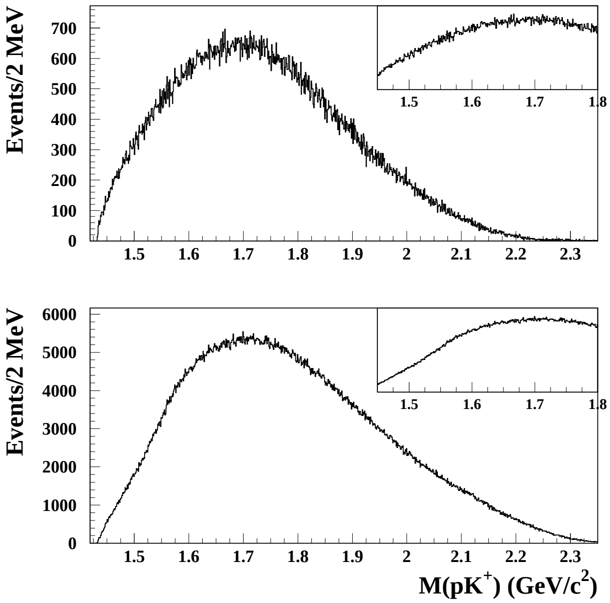

FIG. 3: The pK^+ invariant mass spectra obtained after all cuts were applied, including the removal of the $\Lambda(1520)$ and $\phi(1020)$ events. Upper panel: Case 1 in which all three final state particles, p, K^+ and K^-, were detected. Lower panel: Case 2, in which only the p and K^+ are required to be detected and the K^- is identified by missing mass cuts corresponding to the lower panel of Fig 1. The inset in each panel is a detail in the region near the reported Θ^+ mass where one might expect a peak due to the Θ^{++}. In both cases the spectra appear featureless.

in determining the cross section upper limit $\sigma^{95\%}_{\Theta^{++}}$. The CLAS acceptance, $\epsilon(M_{\Theta^{++}})$ for the detection of the Θ^{++} was obtained by means of a detailed Monte Carlo simulation. The simulation assumed t-channel dominance in which the K^- is mainly produced at forward angles in the center-of-mass system. Assuming that the properties of the t-channel K^- would be similar to that of the K^+ in $\Lambda(1520)$ production, the energy dependence and the t-slope were taken from the experimental $\Lambda(1520)$ photoproduction reaction. The Monte Carlo study showed that the acceptance was almost flat over the full range of $\cos\theta_{CM}$. Thus, even for extremely different event generators, t-channel and u-channel Θ^{++} photoproduction, the calculated acceptances differ by less than 10%. The result of the simulation is that the CLAS acceptance with all the applied analysis cuts varied from 6% at $M_{\Theta^{++}} = 1.5$ GeV/c^2, up to 16% at $M_{\Theta^{++}} = 2.0$ GeV/c^2.

The estimated systematic errors in acceptance were combined with those of the detector inefficiencies, photon flux normalization and Θ^{++} mass resolution to give an overall estimated 15% systematic error in the resulting upper limit.

The resulting upper limit of the scans in $M_{\Theta^{++}}$ and $\cos\theta_{CM}$ for Case 2 using Method 1 is shown in Fig. 4. For both methods we find the average upper limit in the mass region where a isospin partner of a Θ^+ is expected, near 1.54 GeV/c^2, at approximately 0.15 nb, and not much different for the range of photon energies accessed in this experiment in the mass range from 1.5 to 2.0 GeV/c^2.

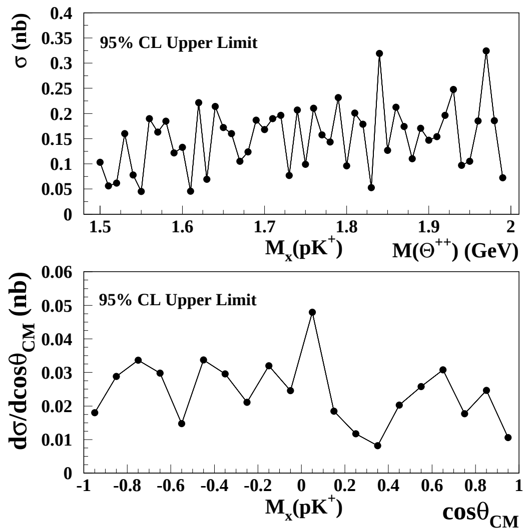

FIG. 4: Upper panel: The calculated upper limit on the cross section at 95% confidence level vs. $M_{\Theta^{++}}$, using the Feldman-Cousins approach, as discussed in the text, for Case 2 in which the K^- was not required to be detected. The upper limit at 95% CL at $M_{\Theta^{++}}$ near 1.54 GeV/c^2 is estimated to be approximately 0.15 nb. Lower panel: The upper limit as a function of $\cos\theta_{CM}$ at $M_{\Theta^{++}} = 1.54$ GeV/c^2. The systematic uncertainty in the magnitude of the upper limit is estimated at 15%.

The upper limit of the ratio $\Theta^{++}/\Lambda(1520)$ was also obtained from the data. The average cross section for $\Lambda(1520)$ photoproduction was calculated from the number of $\Lambda(1520)$ events in a manner similar to that described for $\sigma^{95\%}_{\Theta^{++}}$ above. The result is $\sigma_{\Theta^{++}}/\sigma_{\Lambda(1520)} < 2.3 \times 10^{-4}$ at 95% CL averaged over the photon energy range of this experiment.

The Θ^{++} production cross section may be directly connected with the Θ^{++} width $\sigma_{\Theta^{++}} \sim \Gamma_{\Theta^{++}}$ (see for example [5]). So small a cross section implies a very narrow resonance width. However, an upper limit on the width would be highly model dependent, differing by as much as an order of magnitude for existing approaches [5, 26, 27, 28, 29]. For example, for an isovector pentaquark of $J^P = 1/2^+$ the upper limit on the width implied by the present result for the Regge approach [26] would be $\Gamma < 0.1$ MeV/c^2, while for the effective Lagrangian approach [5] $\Gamma < 0.01$ MeV/c^2.

In conclusion, the present experiment finds no evidence of the formation of a doubly charged pentaquark in the exclusive channel $\gamma p \to K^-\Theta^{++} \to K^-K^+p$. The very high statistical accuracy of the data allows one to obtain

a rather small upper limit on the cross section over a mass range from 1.5 to 2.0 GeV/c^2, with a value of about 0.15 nb at 95% CL near 1.54 GeV/c^2 where a Θ^{++} isovector partner of the Θ^+ might be expected. Such small upper limits on the cross section, and the implied width, makes it likely that the Θ^+ baryon (if it exists) has no isotopic partner and thus is an isosinglet state. Although the present experiment does put very strong limits on the mechanisms which would be required to produce an isovector pentaquark, we point out that it does not access a reaction in which a pentaquark may be produced in association with an additional pion, as in Ref. [13].

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